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# Effective mass and collision time of (100) Si surface electrons

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The effective mass of electrons in (100) Si inversion and accumulation layers was measured by the temperature broadening of oscillatory magnetoconductance technique for a wide range of substrate doping level, geometry, and interface charge as well as various field-strength and substrate biases. It is shown that the apparent effective mass values are very sensitive to these parameters. Measurements were made at constant magnetic field but for varying oxide charge so that for a given magnetic field the effect of oxide-charge scattering could be eliminated by extrapolating to zero oxide charge. The result was remarkably a carrier-concentration independent mass of about 0.21. Collision broadening of the oscillations was studied to determine the scattering time $\tau$. The values of $\tau$ were found to be sensitive to the preexponential damping factor in H. The results are in fair agreement with the zero-field conductivity and average magnetoconductance measurements.

## INTRODUCTION

Recently, there have been many reports regarding the apparent effective mass of electrons in Si (100) inversion layers both experimentally[1-3] and theoretically.[4-7] The interest in this subject is mainly due to the possibility of the experimental verification of many-body effects in this versatile quasi-two-dimensional system, and provides an important testing ground for various theoretical considerations. The technique of determining the effective mass from the temperature dependence of the oscillatory magnetoconductance was first applied in this system by Fowler *et al.*[8] and was extended for a wide range of carrier concentrations by Smith and Stiles.[1] The latter authors found a distinct dependence of the mass on the carrier concentration ($m$ decreases with increasing carrier concentration from $7\times10^{11}$ to $3\times10^{12}$ cm$^{-2}$) in a way qualitatively as expected from many-body considerations for the quasiparticle mass enhancement. It is generally believed that low-frequency conductivity such as the oscillatory magnetoconductance measurements should have quasiparticle behavior resulting from electron-electron interaction whereas high-frequency conductivity as measured in cyclotron resonance experiments should have band electron properties because of the translational invariance of the electron-electron interaction[3] in a homogeneous system. (It was pointed out by Tzoar *et al.*[9] that certain types of scattering may play a role in breaking the translational symmetry and reintroducing Coulomb effects even in high-frequency conductivity such as in cyclotron resonance experiments.) Experimentally, however, there has been some confusion about the mass which appears to depend on a variety of experimental parameters (temperature,[10] frequency, and collision time[3] in cyclotron resonance experiments, carrier concentration,[1] field orientation,[2] etc. in SdH type of measurements).

## MEASUREMENTS–TEMPERATURE BROADENING

Below we report some results on the Shubnikov–de Haas (SdH) type of measurements in metal-oxide-semiconductor field-effect transistors (MOSFET's) indicating that the dependence of the masses determined in this way is ambiguous and may depend on parameters which are not yet understood. Samples used include various levels of doping of substrate, gate oxide thickness, gate oxide charges, substrate biases, magnetic fields, etc. The amplitude of the magnetoconductance as well as the first and second derivatives with respect to gate voltage were carefully measured as a function of the carrier concentrations at a constant magnetic field normal to the surface. The field strength was sufficiently small so that the oscillations were simple sinusoids. This could be checked by observing that the relative amplitude of each derivative as a function of carrier concentration remained unchanged. The field strength was calibrated to better than 0.1% and maintained constant during measurement to better than 0.01%. The drift field in the channel was kept smaller than 0.2 V/cm so that the electron temperature due to hot electron effect extrapolated from the results of Fang and Fowler[11] was less than 0.05 °K. The temperature range for the measurement was between 4.2 to 1.8 °K and its accuracy and stability during measurement was estimated to be better than ±0.01 °K.

The thermal broadening of the transverse magnetoconductance $\sigma_{xx}$ arises from the Fermi-Dirac distribution of the electrons in the Landau levels with a density of state periodicity of $E_F/\hbar\omega_c$ where $E_F$ is the Fermi energy and $\omega_c$ is the cyclotron frequency of the surface carriers. A usual transport calculation with the Fourier analyzed density of states neglecting spin, gives the oscillatory part of the transverse magnetoconductance

$$\sigma_{xx} = \sum_n K_n \frac{2\pi n^2 kT}{\hbar\omega_c} \exp\left(i2\pi n \frac{E_F}{\hbar\omega_c} + \phi\right) \Big/ \sinh \frac{2\pi^2 nkT}{\hbar\omega_c}, \quad (1)$$

where $n = 1, 2, \ldots, K_n$ are the Fourier coefficients and are independent of $T$, and $\phi$ is the phase displacement of the oscillation. The temperature dependence of the oscillation amplitude occurs in both preexponential and sinh factors. If $2\pi^2 kT > \hbar\omega_c$, only the fundamental component of oscillation need be considered. Experimentally, we employed magnetic field strengths between 1.5 and 2.5 T at temperatures between 1.8 and 4.2 °K. Thus, this condition is well satisfied with the cyclotron mass in the neighborhood of $0.2m_0$. The temperature variation of the amplitude can be accurately approximated by an exponential damping factor

$$A \propto T \exp(-2\pi^2 kTm_c/\hbar eH). \quad (2)$$

The effective mass was determined from the temperature dependence of the amplitude at a given magnetic field using this relationship.

Figure 1 shows a typical result for an inversion layer on a (100) surface for a closed-circular-channel geometry, a substrate resistivity of 0.5 Ω cm ($N_a \approx 3 \times 10^{16}$ cm$^{-3}$, where $N_a$ is the acceptor-impurity concentration), and a polysilicon gate electrode with gate oxide thickness 120 Å. It was measured at $H = 2.5$ $T$ for 0 and −3 V substrate bias. The carrier density dependence of the mass has the trend expected from many-body-effect considerations and qualitative agreement with the results of Smith and Stiles.[1] We note that with substrate bias, a reverse bias between the inversion layer and the substrate, the apparent mass is reduced for a given carrier density. This is in apparent disagreement with many-body considerations. The substrate bias reduces the inversion layer thickness, and thus increases the Coloumb interaction because the effective dielectric constant is expected to decrease. Consequently an increased mass enhancement is expected.[4,6]

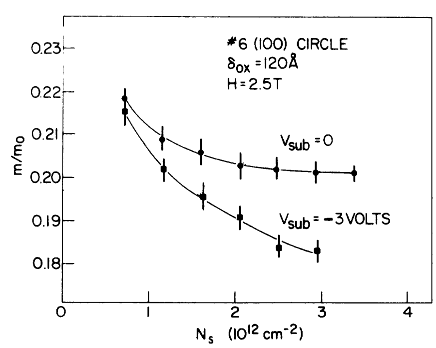


FIG. 1. Typical effective mass as a function of surface carrier concentration of a (100) inversion layer with closed channel. The substrate is $p$-type 0.5 Ω cm. Also shown is the corresponding mass under substrate bias corresponding to depletion charge density of $1.35 \times 10^{12}$ electrons cm$^{-2}$.

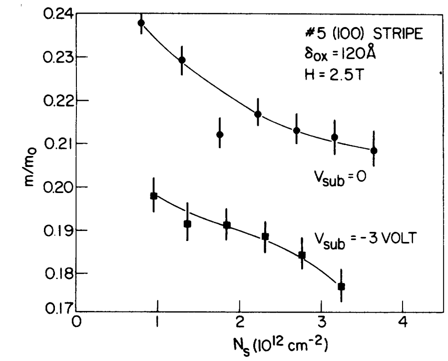


FIG. 2. Effective mass as a function of surface carrier concentration for a sample with open channel. The material, oxide thickness, and measuring conditions are the same as that in Fig. 1.

Several samples with different substrate resistivities as well as different geometries, circular and linear, with different peak mobilities at 4.2 K have been measured. The masses were found to be quantitatively different from sample to sample. However, the general qualitative features were the same. The substrate bias reduces the mass for all the samples. The asymptotic mass at higher carrier density (>$3 \times 10^{12}$ cm$^{-2}$) is also smaller for the substrate bias cases with values for some samples smaller than the band mass of $0.19m_0$. This result is in direct contradiction with that of Lakhani *et al.*,[2] who found that the apparent mass was enhanced by substrate bias.

The results on a different sample measured under the same conditions are shown in Fig. 2. The sample has identical substrate resistivity, oxide thickness, and gate material as in the previously described device except that the conducting channel geometry is an open stripe. The apparent mass decreased with carrier concentration as before, but the results are quantitatively different beyond the estimated error. It is not clear why the open channel geometry should make a marked difference in this measurement. The width-to-length ratio of the channel is about 20. The fringing channel effect due to open ends shows negligible effect on the effective mobility measurements. A possible explanation is that the SdH amplitude is extremely sensitive to the scattering time $\tau$ of the carriers. The inhomogeneous situation near the

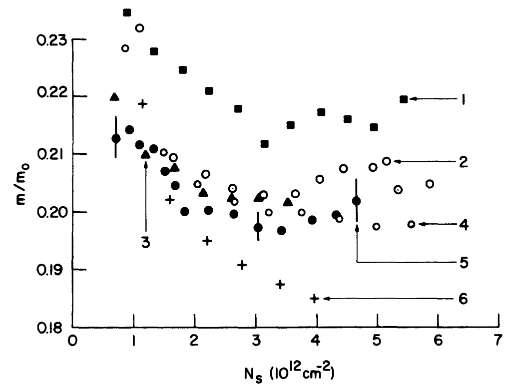


FIG. 3. Collection of the results of mass measurement on (100) inversion and accumulation layers with various substrate doping measured at different field strengths. Samples are identified in Table I.

open ends of the channel as well as exaggerated substrate bias effect in that region may have affected the SdH amplitude sufficiently so that it caused the observed results.

We next examine the variation in substrate doping effect on these measurements. We have measured samples with resistivities ranging from 2 Ω cm $n$-type to 0.5 Ω cm $p$-type, i.e., from accumulation layers with very little minority impurity to inversion layers with various degrees of depletion space charge layers. All samples were closed circular channel structures. A representative collection of the results is shown in Fig. 3. All data are from transconductance (first derivative of the channel current as a function of the gate voltage) measurements. The magnetic fields used ranged from 2.15 to 3.6 T and were chosen for a particular sample to give fundamental sinusoidal oscillations with reasonable amplitudes. As can be seen from the plots, the general feature of decreasing mass with increasing carrier concentration is preserved for all samples shown. Although there exists some grouping in data among the samples, there is a considerable amount of spread of the mass values for a given carrier concentration. Samples 1, 3, 4, and 6 are inversion layers and samples 2 and 5 are accumulation layers. The details about the samples and measuring fields are listed in Table I. It is interesting to note the ion implanted sample (2) whose channel is implanted with $1\times10^{12}/\text{cm}^2$ $^{31}P^+$ ions at 160 keV on a 10-Ω cm $p$-type substrates. This gives an accumulation layer with majority and minority doping of $5\times10^{15}/\text{cm}^3$ and $1.5\times10^{15}/\text{cm}^3$, respectively. The peak mobility of this sample is about 3000 $\text{cm}^2/\text{V}$ sec. This is to be compared with peak mobility of 6500 $\text{cm}^2/\text{V}$ sec of sample 1 which has the same substrate but without ion implants, and also the peak mobility of 10 000 $\text{cm}^2/\text{V}$ sec of sample 5 with accumulation layer whose majority doping concentration is $2\times10^{15}/\text{cm}^3$ and minority doping estimated to be about $10^{14}/\text{cm}^3$.

The results shown in Fig. 3 do not suggest any explicit pattern of substrate doping dependence on the mass values. No particular dependence on the effective mobility of the samples is observed, in general. It remains possible that the amplitude of SdH oscillations depends on the details of the scattering which may not show up significantly in the effective mobility. It is also conceivable that the inhomogeneity in the channel may play a significant role in the amplitude of oscillation. There is no consistency between the substrate doping results and the substrate bias results so far as the depletion layer charge effect on the mass is concerned. Larger substrate doping (more depletion charge) does not consistently result in a smaller effective mass as observed in the substrate bias experiments.

## OXIDE-CHARGE EFFECT ON TEMPERATURE BROADENING

In order to identify the possible role of surface charge scattering effects on the SdH apparent mass, we have examined samples with deliberate $Na^+$ doping in the gate oxide. A controlled amount of $Na^+$

TABLE I. Sample description for Fig. 3.

| Sample | Conduction layer (Inv. or Acc) | Majority substrate impurity concentration ($\text{cm}^{-3}$) | Field at which measurement was made (T) | Oxide thickness (Å) | Note |
|---|---|---|---|---|---|
| 1 | Inv. | $1.4\times10^{15}$ $p$ | 2.5 | 486 | |
| 2 | Acc. | $5\times10^{15}$ $n$ | 3.59 | 468 | $^{31}P^+$ ion imp.ch. |
| 3 | Inv. | $3\times10^{16}$ $p$ | 2.5 | 120 | Si gate |
| 4 | Inv. | $5\times10^{15}$ $p$ | 3.01 | 682 | |
| 5 | Acc. | $2.6\times10^{15}$ $n$ | 2.15 | 540 | |
| 6 | Inv. | $3\times10^{16}$ $p$ | 2.15 | 206 | Si gate |

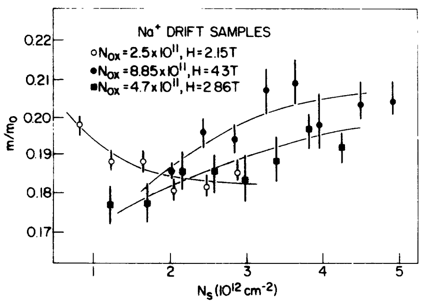


FIG. 4. Effective mass as a function of surface carrier concentration for different interface oxide charge resulting from $Na^+$ ion drift.

can be drifted toward the $SiO_2$-Si interface by means of temperature-bias stress treatment.[12] The $Na^+$ ions near the interface give rise to ionized-impurity-like scattering for the surface electrons. We have measured the apparent mass for a sample which had different effective oxide charge ($Na^+$) at the interface by this technique. The result is shown in Fig. 4 for three different oxide charges: $2.5\times10^{11}/\text{cm}^2$, $4.7\times10^{11}/\text{cm}^2$, and $8.85\times10^{11}/\text{cm}^2$, respectively. At the lowest oxide charge which corresponds to the sample prior to any $Na^+$ drift, the general variation of the mass with carrier concentration is similar to the previously described results although the absolute values differ. After the initial measurements the sample was first drifted to give $8.85\times10^{11}/\text{cm}^2$ of oxide charge. It is seen that the values and the carrier dependence of the mass have changed dramatically. The apparent mass increases with the surface carrier density $N_s$, which is just opposite to all previously reported results. Upon reducing $Na^+$ to $4.7\times10^{11}/\text{cm}^2$ the abnormal dependence of the mass on $N_s$ appears to be reduced. It should be noted that since the effective mobility was markedly reduced by the presence of the $Na^+$ near the interface, the magnetic fields at which the SdH were measured had to be increased to 4.3 and 2.86 T for the oxide charges $8.85\times10^{11}/\text{cm}^2$ and $4.7\times10^{11}/\text{cm}^2$, respectively, from 2.15 T for oxide charge of $2.5\times10^{11}/\text{cm}^2$, so that the amplitude of oscillation could be accurately determined.

Since, the magnetic field at which these data are taken influences the results (see next section), this measurement was repeated using a constant magnetic field of 3.88 T. This choice of field may introduce some uncertainty in the mass at low oxide charge levels, since there is some deviation from a sinusoidal SdH response. However, a lower field would not allow data to be obtained at the high-oxide-charge concentrations. The results of this measurement are shown in Fig. 5. The qualitative features are seen to be similar to the previous results obtained with varying magnetic fields. The behavior at low oxide charge follows that of previously reported results on clean samples, whereas the high-oxide-charge results are qualitatively different. The results shown in Figs. 4 and 5 clearly demonstrate the importance of scattering of the electrons to the apparent mass seen from SdH experiments.

This last set of data has been used to obtain a mass extrapolated to zero-oxide-charge scattering. The extrapolation was done for the actual SdH amplitudes, since we can no longer trust the SdH theory [Eqs. (1) and (2)] when scattering is important. This left an amplitude $A_0$ which is the SdH amplitude in the absence of oxide charge scattering. These amplitudes were then analyzed in the same way as all the previous data and a mass was obtained. Figure 6 shows the resultant mass as a function of $N_s$. This procedure gives a mass which is essentially independent of carrier density. However, this mass is perhaps no more meaningful

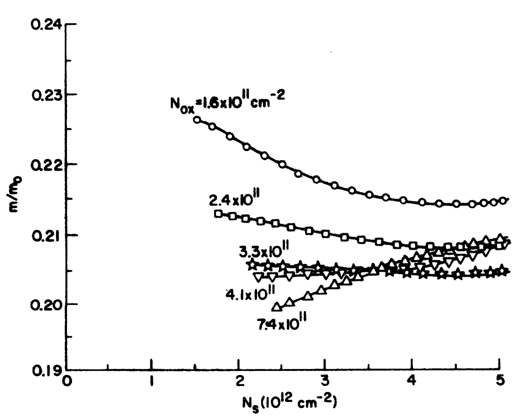


FIG. 5. Effective mass as a function of carrier concentration measured using samples with different oxide charges ($N_{ox}$) all measured at 3.88 T.

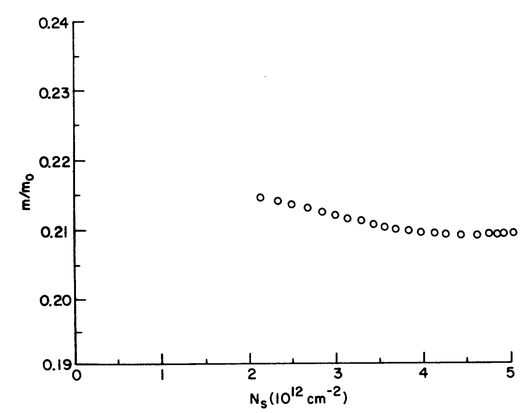


FIG. 6. Effective mass derived by extrapolating the SdH amplitudes to zero oxide charge.

than any of the other apparent masses, since surface roughness scattering is still present. It does, however, further demonstrate the importance of scattering on the mass determinations.

## FIELD DEPENDENCE OF TEMPERATURE BROADENING

The foregoing discussions are all based on data assuming [as expected from Eq. (2)] mass being independent of the magnetic field at which it was measured. However, we have surprisingly found through a systematic study at various magnetic fields, the SdH-determined apparent mass depends on the field strength. Figure 7 shows the carrier-concentration-dependent mass at four field strengths: 1.50, 1.88, 2.26, and 2.64 T for an accumulation layer. The fields are small enough for all cases such that the oscillations in the temperature range measured are all simple sinusoids. Data were computer fitted according to Eq. (2). Most of the mass values have a possible error of ~1%. Thus the results shown in Fig. 7 are statistically significant. Generally, we found that for a given carrier concentration, the "mass" increases with increasing field. In light of this result, it is evident that the previously presented data which were measured at different fields should be read with caution. This finding further clouds the criterion as far as the proper choice of magnetic field is concerned in this type of measurements.

We have measured several samples with different substrate resistivities, and also using different channel conductivity methods, i.e., various derivatives with respect to the gate voltage $i_d$, $i_d'$, and $i_d''$. The general features of the field dependence were found to be similar for each of the measurements. If the scattering mechanism is important for these measurements, the data would suggest that the value of $\omega_c\tau$ affects the amplitude exponent shown in Eq. (2). We have reanalyzed the observed mass values as a function of $\omega_c\tau$ for all measured values. $\tau$ used in this analysis is from dc conductivity and low-field magnetoconductance. (This is discussed in a later section.) Figure 8 shows the data replotted as a function of $\omega_c\tau$. We note that there are good correlations in two regions, namely, $\omega_c\tau < 0.8$ and $\omega_c\tau > 1.5$. Mass is seen to increase with $\omega_c\tau > 1.5$ and drop sharply for $\omega_c\tau < 0.8$. Between these two regions, very little correlation is in evidence. Near $\omega_c\tau \simeq 1$, data show a large spread in mass values. For a given value of $\omega_c\tau$, the dependence of mass on carrier concentration is opposite to the dependence described previously. Figure 9 shows some examples of this representation.

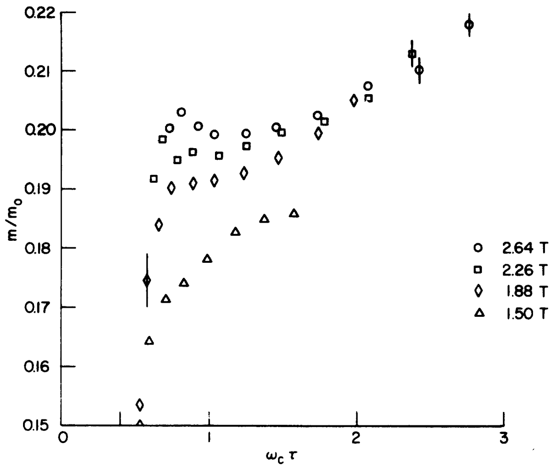


FIG. 8. Effective mass values in Fig. 5 replotted as a function of $\omega_c\tau$.

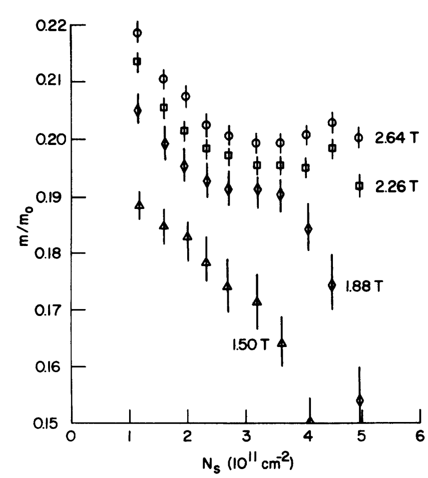


FIG. 7. Effective mass determined from various magnetic field strengths for an accumulation layer.

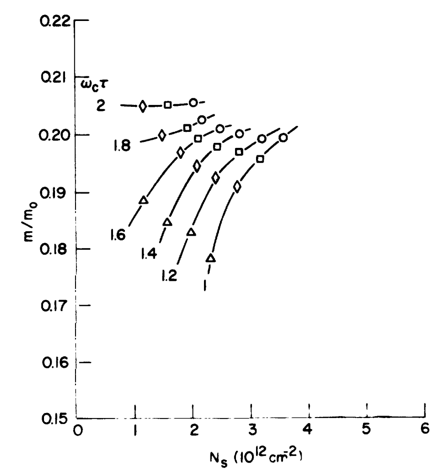


FIG. 9. Effective mass as a function of surface carrier concentration with $\omega_c\tau$ as parameters.

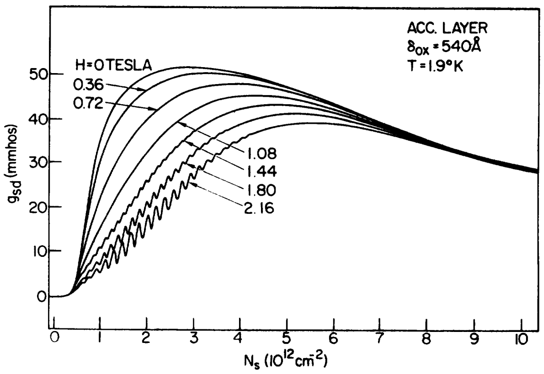


FIG. 10. Channel conductance $g_{sd}$ as a function of surface carrier concentration at various magnetic fields at 1.9 °K. Oscillatory behavior is seen for the field above 1.08 T.

## COLLISION BROADENING

The apparent inconsistency of the mass determination described above casts serious questions on the adequacy of the amplitude exponent in formulas (1) and (2) which were widely used for this purpose. A possible source of inconsistency may be in the collision broadening of the Landau levels, which may affect the temperature damping in an implicit way. Dingle has shown[13] that for a Lorentzian line shape whose width Γ can be expressed in terms of a phenomenological scattering time as $\hbar/2\tau_i$, the amplitude of the diamagnetic oscillatory phenomena should contain a damping factor $\exp(-\pi/\omega_c\tau_c)$ and the fundamental component of the oscillatory transverse magnetoconductance of Eq. (2) is given by

$$\Delta\sigma_{xx} = \frac{e^2N_s\tau}{m}\frac{1}{1+\omega_c^2\tau^2}f(\omega_c)\frac{2\pi^2kT}{\hbar\omega_c}\left(\cos\frac{E_F}{\hbar\omega_c}+\phi\right) \times \exp\frac{-\pi}{\omega_c\tau}\left(\sinh\frac{2\pi^2kT}{\hbar\omega_c}\right)^{-1}, \quad (3)$$

where $e^2N_s\tau/m(1+\omega_c^2\tau^2)$ is just the low-field ($\omega_c\tau \ll 1$) magnetoconductance, $f(\omega_c)$ is a preexponential collision damping factor, and $2\pi^2kT/\hbar\omega_c$ is the preexponential temperature broadening factor. Thus the field dependence of the oscillatory conductivity gives information on the phenomenological scattering time $\tau$.

In order to examine the behavior of the amplitude of the oscillation properly, the entire preexponential factor must be adequately evaluated. We have studied the low-field magnetoconductance as well as the moderate field oscillatory regime ($0.5 < \omega_c\tau < 2.5$). Figure 10 is a typical channel conductance as a function of carrier concentration for various magnetic fields at 1.9 °K. For the field smaller than 1.08 T, where no oscillation is apparent, the conductance $\sigma_{xx}$ at any given carrier concentration $N_s$ is given by $\sigma_0/(1+\omega_c^2\tau^2)$, where $\sigma_0 = e^2N_s\tau/m$. Above 1.4 T, SdH oscillations begin in the carrier concentration where the mobility is high. However, the mean value of the oscillatory conductance $\bar{\sigma}_{xx}$ at any given field obeys the low-field behavior. This is shown in Fig. 11 where we plot $(\sigma_0/\bar{\sigma}_{xx} - 1)^{1/2}$ as a function of $H$ for any given carrier concentration. The straight line indicates $\bar{\sigma}_{xx} = \sigma_0/(1+\omega_c^2\tau^2)$, where the slopes gives scattering time $\tau$. The values of $\tau$ obtained in this way are shown in Fig. 12 together with values obtained from zero-field-conductivity measurements. A mass of 0.19 was assumed. The agreement between these two measurements is quite satisfactory.

The amplitude $A$ of the oscillatory conductance for $2\pi^2kT > \omega_c\tau$ may then be given by

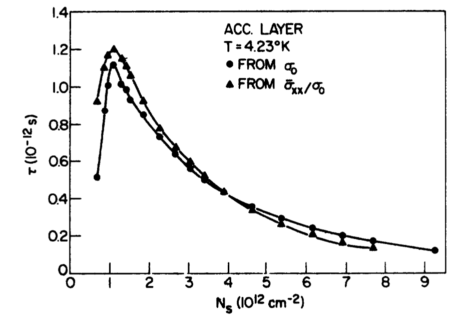


FIG. 11. Plot of $(\sigma_0/\bar{\sigma}_{xx} - 1)^{1/2}$ as a function of the field showing the average magnetoconductance $\sigma_{xx}$ obeys low-field magnetoconductance behavior.

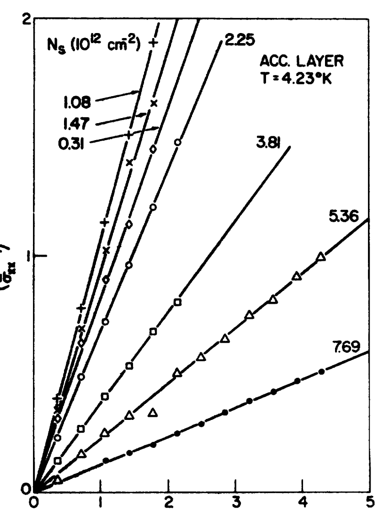


FIG. 12. Surface carrier scattering time $\tau$ as a function of carrier concentration as measured from the average magnetoconductance. $\tau$'s deduced from zero field conductivity are also shown for comparison.

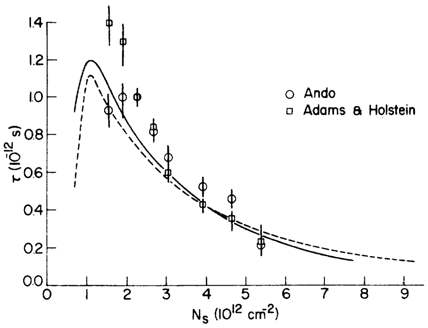


FIG. 13. Scattering time $\tau$ as a function of surface carrier concentrations from collision broadening measurements fitted with theories of Ando and of Adams and Holstein. Zero field and average magnetoconductance determined $\tau$'s in dashed and solid curves, respectively, are also shown for comparison.

$$A=\bar{\sigma}_{xx}f(\omega_c)\frac{2\pi^2kT}{\hbar\omega_c}\exp\left(\frac{-\pi}{\omega_c\tau}\right)\exp(-2\pi^2kT/\hbar\omega_c)$$
$$=\bar{\sigma}_{xx}f(\omega_c)\frac{2\pi^2kT}{\hbar\omega_c}\exp\frac{\pi}{\omega_c}\left(\frac{1}{\tau}+\frac{1}{\tau_T}\right), \quad (4)$$

where $\tau_T\equiv\hbar/2\pi kT$ is the temperature broadening equivalent time. In Ando's self-consistent calculation,[14]

$$f(\omega_c)\sim\frac{4\omega_c^2\tau^2}{1+\omega_c^2\tau^2}=\frac{\bar{\sigma}_{xx}}{\sigma_0}\omega_c^2\tau^2 . \quad (5)$$

Thus, at any given carrier concentration and temperature

$$A\sim\left(\frac{\sigma_{xx}}{\sigma_0}\right)^2\omega_c\tau^2\exp\left(-\frac{\pi}{\omega_c\tau_{eff}}\right), \quad (6)$$

where we have defined $\tau_{eff}^{-1}\equiv\tau^{-1}+\tau_T^{-1}$. Since $\bar{\sigma}_{xx}/\sigma$ is a readily measurable quantity, the magnetic field dependence of the amplitude can be fitted to Eq. (6) with no fitting parameter. Figure 13 shows the $\tau$ obtained this way where a constant cyclotron mass of $0.19m_0$ is used.

The same field-dependent data were evaluated with the theories of Adams and Holstein[15] and Kubo, Miyake, and Hashitsume.[16] Since our data are in the regime of large Landau quantum numbers ($n>3$) and $\hbar\omega_c$ smaller than $2\pi^2kT$, inter-Landau level scattering becomes an important broadening mechanism. The amplitude function can be written as

$$A\sim\left(\frac{\sigma_{xx}}{\sigma_0}\right)\left(\frac{\hbar\omega_c}{2E_F}\right)^{1/2}\frac{T}{\hbar\omega_c e}\exp\left(-\frac{\pi}{\omega_c\tau_{eff}}\right)$$
$$\sim\left(\frac{\sigma_{xx}}{\sigma_0}\right)\omega_c^{-1/2}\exp\left(-\frac{\pi}{\omega_c\tau_{eff}}\right). \quad (7)$$

This can also be fitted with all measured quantities. Using a cyclotron mass of $0.19m_0$, $\tau$ as a function of $N_s$ obtained in this way is also shown in Fig. 13 together with the zero field and average magnetoconductance deduced values. It should be noted here that Eqs. (6) and (7) are for the conductivity oscillations. In the case of transconductance or field effect mobility oscillation measurements, an additional preexponential factor $\omega_c$ should be multiplied to these expressions. This results from differentiating the sinusoidal factor in Eq. (2).

In view of the uncertainty involved in these measurements and function fitting, the agreement of conductivity $\tau$ and SdH damping $\tau$ from both results are surprisingly good. The small differences between Ando's and Adam and Holstein's theories are not considered significant although the latter appears to agree better with the conductivity $\tau$ at smaller values of $\omega_c\tau$. However, there is no *a priori* reason to expect the conductivity $\tau$ should agree with the SdH-deduced $\tau$. Therefore, the observed agreement in various degree does not provide a valid basis for verification of the theories. What is surprising is the fact that the SdH-deduced $\tau$'s are larger than the conductivity $\tau$ for both theories in a large range of carrier concentrations. Since the SdH and de Haas–van Alphen (dHvA) effects are generally more sensitive to small angle scattering than the electric conductivity, one usually finds that the SdH and dHvA derived collision time $\tau$'s are smaller than the conductivity $\tau$, at least in most of the reported measurements in three-dimensional systems.[17,18] The fact that the two-dimensional and three-dimensional SdH results have the qualitative differences in comparison with the respective conductivity measurements and the existence of the phenomenological collision damping $\tau$ manifested by the exponential field dependence of the amplitudes, leads one to believe that the preexponential factor in $H$ plays an important role in the $\tau$ determination.

## DISCUSSION AND CONCLUSION

From the above reported widely variable apparent mass values measured, though there is no clear simple pattern, some observations can be made with respect to the results. A negative substrate bias reduces the average distance of the electrons from the interface, $Z_{av}$,[19] as well as the effective inversion layer width, but the observed variation of $m$ with the substrate bias is that it decreases with decreasing inversion layer width. This is in direct contradiction to the many-body-effect prediction[4-7] which results from a decrease in effective dielectric constant and a narrowing of the inversion layer electron distribution with substrate bias. However, associated with decreasing inversion layer width there is an increase in the interface scattering. One is led to believe that scattering must also affect the formalism from which the mass was determined. In some representative cases of our experiments, the apparent mass is generally found to be smaller for lower mobility samples. In fact the mass is found to be proportional to $\omega_c\tau$ for $\omega_c\tau \geq 1.5$. It is tempting to suggest that the apparent mass increases with $\tau$. This results in a mass variation in conflict with the dependence on the substrate bias: increases with substrate bias from the many-body effect and decreases with it from the scattering effect. The observed widely varied mass could possibly result from these two conflicting dependences on the substrate bias.

On the other hand, for an accumulation layer, with larger $Z_{av}$ than its inversion layer counterpart, the apparent mass is not generally larger than those of inversion layers under substrate bias. This inconsistency may also be reconciled if the mass enhancement due to the many-body effect caused by decreasing $Z_{av}$ is quantitatively different from the mass reduction caused by increasing scattering.

The apparent mass was also found to increase with increasing field strength at which the mass was measured. In particular, it has some degree of correlation with $\omega_c\tau$. We believe this is a significant source which contributes to the inconsistency of the mass determination which assumes no $\omega_c\tau$ dependence.

The collision broadening $\tau$ evaluated from the field-dependent oscillatory magnetoconductance shows that the values obtained are sensitive to the preexponential factor fitting. The agreement between the oscillatory and average magnetoconductance results is rather surprising. Since it is not known what the relationship is between the dc conductivity and the collision relaxation times, it is not possible to conclude which theory regarding the collision broadening is more appropriate from the present data. The fact that SdH-deduced relaxation time is somewhat larger than the conductivity $\tau$ may also be related to the apparent mass variation since in determining $\tau$ through the damping exponent $\pi/\omega_c\tau_{eff}$ we have assumed a constant cyclotron mass of $0.19m_0$. Thus, strictly speaking we were determining $\tau_{eff}/m_c$. It follows then, $\tau^{-1} = \tau_{eff}^{-1} - \tau_T^{-1}$ should be affected by the cyclotron mass used in the analysis.

The widely variable apparent mass observed was shown to depend on a number of experimental and sample parameters. This clearly indicates the inadequacy of the present theory at least concerning the amplitude of oscillation.[23] Among others, the possible difficulties may be that the mass for thermal broadening is different from that of the collision broadening. If scattering is important in the mass determination as suggested by the experiment, then carrier screening of the long-range electrostatic interaction by the degenerate electron gas should be important in the mass determination.[20] Spin splitting which was neglected in Eq. (2) may be particularly important in the inversion layer in that the $g$ factor varies with carrier concentration.[21] It is of course possible that either the mass or the scattering time is temperature dependent. The cyclotron resonance experiments of Küblbeck and Kotthauss[22] do not indicate such a dependence in the carrier concentration range studied. The scattering time in the absence of magnetic field is only weakly dependent on temperature and that part due to oxide charge scattering has been shown by Hartstein and Fang[23] to be temperature independent. Thus the only remaining possible extraordinary temperature dependence using the standard formulation must arise from a temperature dependence of the surface roughness scattering in the presence of a magnetic field. The possibility remains that the standard formulation is wrong.

Our measurements indicate that the apparent mass determined from the oscillatory magnetoconductance should be used with caution. It probably is not adequate in the present form to confirm the validity of different existing many-body calculations.

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